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Torrefaction of beechwood: A parametric study including heat of reaction and grindability

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HIGHLIGHTS

- ▶ Beechwood chips are torrefied at lab scale with different parameters.
- ▶ Mass loss of the dry solid is a good indicator for the degree of torrefaction.
- ▶ Heat consumption of the reactor is measured to determine the heat of reaction.
- ▶ The heat of reaction ranges from −199 J/g (exothermic) to 148 J/g (endothermic).
- ▶ Grindability in terms of HGI is moderate or easy for solid mass loss >30%.

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ABSTRACT

Torrefaction describes a thermal treatment of biomass in order to obtain a solid product with more or less coal-like properties. Therefore a mild pyrolysis in an oxygen-free atmosphere is applied. In this work beechwood was used as feedstock because of its consistent quality in commercially available chips. A parametric study was conducted with a continuously working, indirectly heated reactor having a throughput on the order of 1 $\text{kg}_{\text{product}}$/h, wherein each parameter was varied independently. The reactor temperature ranged from 270 to 300 °C, residence time from 20 to 60 min, and feed moisture content from 0% to 20%. Ultimate and proximate analysis of the products as well as grindability tests have been performed. Additionally, the integral heat of reaction was determined for each test run by measurement of the heat consumption of the reactor. Mass loss of the dry solid is shown to be a good indicator of the degree of torrefaction and ultimate as well as proximate analysis show good agreement with existing literature data. Grindability in terms of HGI depends on the degree of torrefaction and reaches from difficult to grind to very easy to grind. In terms of beater wheel mills used for combined drying and milling in lignite fired power plants, grindability is poor and in general worse than that of Rhenish lignite. The heat of reaction is found to be close to the border between endo- and exothermic with a trend to more exothermic behaviour for increasing degree of torrefaction. Despite the uncertainty of the heat capacity of wood and torrefied wood above a temperature of 420 K, the determined heat of reaction is found to be in the range of −199 J/g (exothermic) to 148 J/g (endothermic) for all tests with spans of about ±70 J/g for each single test run. Besides severe torrefaction, caused by a high reactor temperature, an increased residence time is found to cause a remarkable exothermic heat of reaction.

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1. Introduction

Biomass is a source of renewable energy, which can be converted to heat and power in line with demand. This is an advantage over photovoltaic and wind power making biomass an important pillar in the energy supply today and in the foreseeable future. However, the energetic usage of biomass is challenging, since transport over large distances is often not viable due to its low heating value, the grindability is not sufficient for milling with existing equipment, e.g. in coal-fired power plants and, furthermore, storage is difficult due to micro organisms causing decay. To overcome these challenges torrefaction has been proposed as a process for upgrading biomass by thermal treatment [1–3]. Torrefaction is a kind of mild pyrolysis, typically utilizing temperatures ranging from 200 to 300 °C and residence times in the magnitude of a few minutes to about one hour. To avoid combustion, torrefaction has to take place in the absence of oxygen. Ciolkosz and Wallace [4] published a review paper in 2011

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summarizing most of the available literature about torrefaction. Numerous publications have already addressed the change in chemical composition and model development to predict decomposition rates. Nevertheless, literature dealing with the following two important aspects of torrefaction is quite rare:

1. Grindability in units the consumers need.
2. Energy demand and heat of reaction during torrefaction.

The objective of this work is to give an overview of the influence of torrefaction temperature and residence time on important fuel parameters like chemical composition, heating value and grindability. Additionally, the energy demand of the torrefaction reactor is measured to determine the heat of reaction, which is an important parameter for the control of large scale torrefaction plants.

2. Experimental setup

Beechwood chips without bark have been used as raw material for the torrefaction experiments since they can be purchased with relatively constant quality except for the moisture content. The latter varied between 5% and 15%, hence the feedstock has been dried at 105 °C until the weight kept constant and then remoistened to the desired moisture content. The thickness of these chips is about 2 mm, the particle size determined via sieve analysis is given in Table 1.

Torrefaction experiments were performed with a lab-scale continuously working reactor consisting of a horizontal pipe (length: 1000 mm, diameter: 160 mm) with a screw-conveyor for precise control of the residence time (Fig. 1).

The beechwood chips are fed from a storage container (not shown) to the reactor by a rotary feeder and leave by gravity to a collecting vessel (not shown). To keep the reactor free of oxygen and guide the volatiles to their outlet, flows of technical nitrogen (99.5% purity) are applied to both, the storage container as well as the collecting container. Flow rates are 1 and 0.5 standard litres per minute, respectively. Heating is accomplished indirectly by hot air flowing through the annular gap between the inner and outer pipe in cocurrent flow with the wood chips. Inlet and outlet of this air are shown in the top view in Fig. 1.

Feeder and screw are driven by individual motors allowing for basically independent setting of mass flow (feeder setting) and residence time (screw setting). However, since the filling degree of the screw is limited, the settings are not fully independent from each other (compare Table 2, Test ID 6).

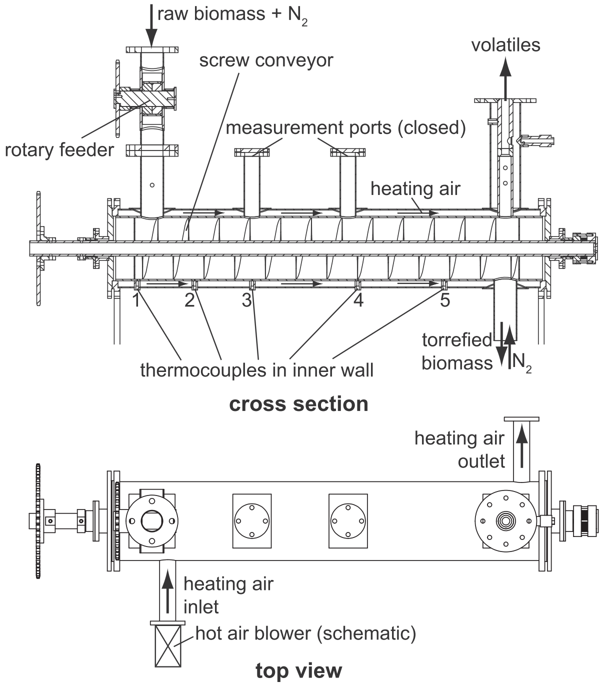

Fig. 1. Sectional view and top view of the utilised torrefaction reactor.

Table 2
Overview of torrefaction parameters of the conducted tests.

Test ID	temperature (°C)[a]	Residence time (min)	Feed moisture (wt.%)	Feeder setting (kg/h)[b]
1	280	40	10	3
2	270	40	10	3
3	290	40	10	3
4	300	40	10	3
5	280	20	10	3
6	280	60	10	2[c]
7	280	40	0	3
8	280	40	20	3
9	300	15	0	8

[a] This temperature is the average of temperatures 2–5 in Fig. 1, compare also Fig. 2.
[b] Since the feeder was calibrated with wood pellets, the real feed mass flow is lower. It is approx. 0.45 multiplied with the stated values.
[c] To avoid jamming of the screw, the mass flow had to be reduced for a residence time of 60 min.

3. Theory and experiments

3.1. Torrefaction

A parameter variation has been conducted to expand the data for torrefaction behaviour of woody biomass. Reproducibility of tests with the utilised reactor is high as has been proven in previous tests [5], hence no repetitions were performed. To keep the number of tests small, a reference has been defined and starting from this, the parameters temperature, residence time and moisture content of the feed have been varied. Since several authors (e.g. Arcate [6], Bergman et al. [1] and Pach et al. [7]) stated 30% mass loss of the dry mass as typical, reference parameters based on preliminary tests were chosen, which (approximately) match this typical mass loss. The chosen reference parameters were a reactor temperature of 280 °C (average of temperatures 2–5, compare Fig. 1), a residence time of 40 min and a feed moisture content of 10 wt.%. An overview of the tests conducted is given in Table 2.

The mean reactor temperature was kept constant at the desired torrefaction temperature by a controller, which sets the electrical heating power and thus the temperature of the (constant) heating air mass flow.

Table 1
Particle size of raw beechwood chips.

Sieve size (mm)[a]	10	8	6.3	5	3.15	2	1	0.63	0.315
Fraction < sieve (wt.%)	1.57	14.4	28.6	48.4	6.87	0.08	0.01	0.02	0.01

[a] Test sieves according to ISO 3310–1 have been used.

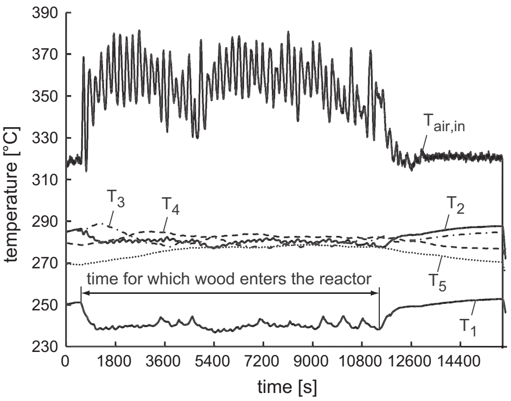

Fig. 2. Temperature profiles during the reference test (ID 1).

To give an indication of temperature profiles in the reactor during a test, the data logged during the reference test (Test ID 1) are given in Fig. 2. Since the measurement position of temperature 1 is cooled by incoming feedstock (which enters at room temperature) this measurement can be used as indication for feedstock entering the reactor. The small upward peaks indicate slight irregularities in the feed flow. Temperatures 2–5 show the temperature distribution in the torrefaction zone. After the start-up phase the maximum spread between these temperatures is well below 10 K. The average of these four temperatures is kept at 280 °C for the reference test (compare Table 2) by control of the heating air inlet temperature $T_{\text{air,in}}$. The frequency of the fluctuations in this temperature is that of the revolution of the screw. This is caused by the impact of biomass in the reactor on the temperature measurements when being conveyed over them. Since the heating air mass flow is constant, the air inlet temperature indicates the heating power of the electrical heater. Irregularities in the feed flow have thus an impact on this temperature causing a slight decrease even before the end of biomass feeding.

Ultimate and proximate analysis of the product have been carried out for all tests except test 9. In order to investigate the impact of torrefaction on the ash composition, detailed ash analyses of raw beechwood and of the product of test 3 have been conducted. The product of test 3 was chosen since it was severely, but not over-torrefied. Since the feedstock for this test was taken from the same charge as the sample of raw beechwood, a comparison of both analyses should show whether torrefaction influences the ash composition or not. Due to the low ash content of beechwood a sample size of 500 g was used for each analysis.

3.2. Grindability

In order to determine the grindability of torrefied wood, two different tests have been performed:

1. Determination of hardgrove grindability index (HGI).
2. Determination of crushing ratio utilizing a special test mill.

The Hardgrove Index is a measure for the grindability of hard-coals [8], which are often milled with vertical roller mills in hard coal fired power plants. Since especially the density of torrefied wood differs from hard coal, the test procedure had to be modified: The samples were milled with a cutting mill utilizing a 4 mm sieve for preparation. The fraction of 0.2–2 mm (standard: 0.6–1.18 mm) was sieved and 20 g (standard: 50 g) were used for milling, since 20 g torrefied wood have an approximate volume of 70 cm^3, which is equivalent to that of 50 g hard coal. After 60 rounds with the Hardgrove mill, the sieving residue on the 0.075 mm sieve was used to calculate the HGI. To check the impact of the modification in the utilised size fraction, a test with a standard hard coal with HGI 39 has been performed with the fraction 0.2–2 mm. Since the resulting HGI value was 39, this modification does not impair the significance of the obtained HGI values.

In lignite fired power plants, milling and drying is often performed simultaneously in beater wheel mills. Due to their different milling principle, HGI-values do not indicate the grindability of lignite for these mills acceptably. Hence, Alstom and RWE developed a procedure and a test impact mill to determine an impact grindability index (PMI) for lignite, which is a good indicator for grindability in large scale beater wheel mills [9]. This test mill was used to determine crushing ratios, which are defined as average particle size before “milling” divided by average particle size after “milling”. Testing was performed directly with the (torrefied) wood chips without prior size reduction.

3.3. Heat demand of torrefaction

In order to determine the heat of reaction during torrefaction, it is necessary to know the heat flow entering the reactor. The following approach has been used to determine this heat flow: A sketch of the reactor and the heat fluxes is given in Fig. 3.

The required value $\dot{Q}_{\text{reactor}}$ is calculated by:

$$\dot{Q}_{\text{reactor}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} - \dot{Q}_{\text{loss}} \tag{1}$$

Since the heat loss to the ambience $\dot{Q}_{\text{loss}}$ is very difficult to calculate, it was measured by a no-load operation in which $\dot{Q}_{\text{reactor}}$ equals zero: For each test, the mean temperature of the reactor was kept constant for about one more hour after the reactor was emptied (compare Fig. 2). The heat loss during this no-load operation can be calculated by:

$$\dot{Q}_{\text{loss,no-load}} = \dot{Q}_{\text{in,no-load}} - \dot{Q}_{\text{out,no-load}} \tag{2}$$

For both cases (load and no-load) $\dot{Q}_{\text{in}}$ is the power consumption of the hot air blower P_{blower}, which is constantly measured. To calculate the mass flow of the heating air, the average heat capacity $\overline{c_p}_{,\text{air}}(T_1, T_2)$ between temperatures T_1 and T_2 is needed, which is calculated by

$$\overline{c_p}_{,\text{air}}(T_1, T_2) = \frac{\int_{T_1}^{T_2} c_{p,\text{air}}(T)\, dT}{\int_{T_1}^{T_2} dT} \tag{3}$$

where $c_{p,\text{air}}(T)$ is the specific heat capacity of air as a function of temperature [10]. With $\overline{c_p}_{,\text{air}}$ the mass flow of the heating air $\dot{m}_{\text{air}}$ is calculated by

$$\dot{m}_{\text{air}} = \frac{P_{\text{blower}}}{\overline{c_p}_{,\text{air}}(T_{\text{amb}}, T_{\text{in}}) \cdot (T_{\text{in}} - T_{\text{amb}})} \tag{4}$$

where T_{amb} is the ambient temperature. With knowledge of the air mass flow, the heat flow of the exiting air can be calculated:

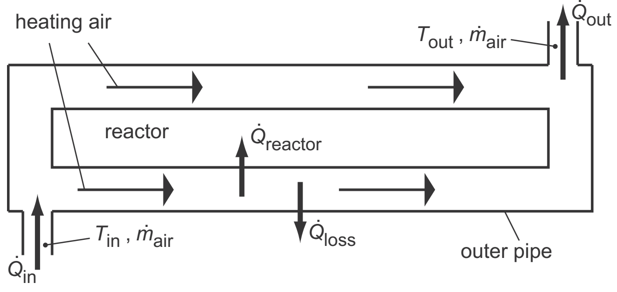

Fig. 3. Sketch of the reactor and the incoming and exiting heat flows.

$$\dot{Q}_{\mathrm{out}} = \dot{m}_{\mathrm{air}} \cdot \overline{c_{p}}_{,\mathrm{air}}(T_{\mathrm{amb}}, T_{\mathrm{out}}) \cdot (T_{\mathrm{out}} - T_{\mathrm{amb}}) \tag{5}$$

The value of the heat loss during torrefaction is calculated by

$$\dot{Q}_{\mathrm{loss,torr}} = \dot{Q}_{\mathrm{loss,no\text{-}load}} \frac{\Delta T_{\mathrm{ln,torr}}}{\Delta T_{\mathrm{ln,no\text{-}load}}} \tag{6}$$

where $\Delta T_{\mathrm{ln,i}}$ is the mean logarithmic temperature difference between the heating air (T_{in} and T_{out}) and the ambience (T_{amb}). Since temperatures and power consumption of the hot air blower are not constant, for each test these values were averaged over a time interval of 20 min. The feed mass flow is calculated by the overall feed mass divided by the time during it was fed to the reactor (see Fig. 2). With known mass flow $\dot{m}_{\mathrm{feed}}$ the heat consumption per feed mass q_{c} can be calculated by

$$q_{\mathrm{c}} = \frac{\dot{Q}_{\mathrm{reactor}} - \dot{Q}_{\mathrm{N_2}}}{\dot{m}_{\mathrm{feed}}} \tag{7}$$

where $\dot{Q}_{\mathrm{N_2}}$ is the heat required to heat up the nitrogen flow from ambient to torrefaction temperature. The (integral) heat of reaction is derived from the specific heat consumption q_{c} via

$$\Delta h_{\mathrm{R}} = q_{\mathrm{c}} - \frac{M}{100} \cdot \Delta h_{\mathrm{V}} - q_{\mathrm{s}} - q_{\mathrm{model}}, \tag{8}$$

where M is the feed moisture content in %, Δh_{V} the enthalpy of vaporisation at 100 °C, q_{s} the required heat to superheat the resulting steam to torrefaction temperature and q_{model} the heat for heating up the solid. Calculation of the latter is complicated for two reasons:

1. The heat capacity of wood is available only up to 420 K (147 °C) due to the fact that above this temperature pyrolysis sets in.
2. The heat capacity of moist wood contains a term which accounts for the binding force between water and wood.

The second constitutes a problem since the feed was dried to 0% moisture and remoistened, which might lead to a modified binding force compared to originally moist wood. Therefore four different models are used to calculate the heat of reaction: Model 1 estimates the most endothermic heat of reaction by neglecting the effect of the binding force between water and wood and by using the heat capacity of charcoal for temperatures above 420 K. Model 2 estimates the most exothermic heat of reaction by accounting for the binding force between water and wood and by extrapolating the heat capacity of (dry) wood for temperatures above 420 K. Model 3 uses the averaged heat capacity of char coal and (extrapolated) wood above 420 K and neglects the binding force between water and wood. Model 4 resembles Model 3, but accounts for the binding force between water and wood. Fig. 4 shows the different heat capacities over temperature and illustrates exemplarily for Model 4, which heat capacities are used in which temperature region. The heat capacity data for wood is taken from [11] and that for charcoal from [12].

4. Results and discussion

4.1. Torrefaction

Englisch [13] stated that the degree of relative volatiles reduction, defined as

$$\mathrm{Torrefaction} = 100 - \frac{V_{\mathrm{dry,torr}}}{V_{\mathrm{dry,raw}}} \cdot 100, \tag{9}$$

is a good indicator for the degree of torrefaction. In particular, for the comparison of different biomasses this is probably a reasonable approach. In this work beechwood is investigated exclusively and therefore the normalized mass loss of the solid is used as degree of torrefaction. Mass loss measurement is possible as torrefaction was performed batchwise; in a continuously operating process measurement of the mass loss is hardly feasible.

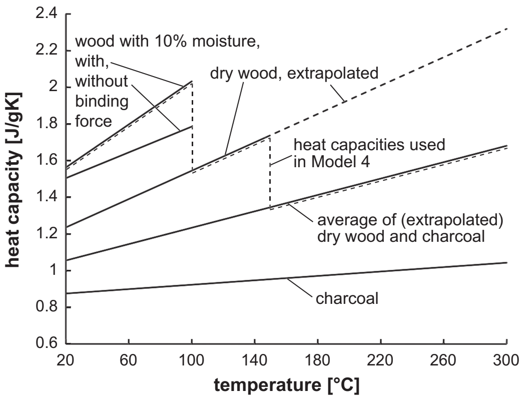

Fig. 4. Heat capacities of dry wood, moist wood and charcoal as well as illustration which are used in Model 4.

The lower heating values (LHVs) (calculated from measured HHV) as well as the energy yields of the solid are plotted against this mass loss in Fig. 5. All data relate to the dry ash-free (daf) basis.

Heating values increase almost monotonously with mass loss and range from 21.1 MJ/kg for sample 5 to 25.3 MJ/kg for sample 4. The trend is even smoother compared to a plot over relative volatiles reduction, hence, at least for beechwood, mass loss of the solid seems to be a good indicator for the degree of torrefaction. The influence of residence time is less influential than that of temperature, especially between 290 °C and 300 °C mass loss and heating value increase strongly. Feed moisture content influences the residence time of the wood at torrefaction temperature and thus has a similar influence like the change in residence time. However, in comparison with the other variations a low moisture content of the feed (sample 7) appears favourable for achieving a high heating value at a specific mass loss. This might be caused by the steam flow resulting from moisture, which purges the volatiles out of the reactor and thus weakens secondary char reactions between volatiles and solid. According to Gomez et al. [14] these reactions cause higher char yields. Consequently, due to the high heating value of char this might result in higher heating values for the torrefied wood.

Since energy efficiency is always important, the energy yield in the solid has to be taken into account, which is defined as:

$$\mathrm{Energy\ yield} = \frac{m_{\mathrm{torrefied}} LHV_{\mathrm{torrefied}}}{m_{\mathrm{raw}} LHV_{\mathrm{raw}}} \tag{10}$$

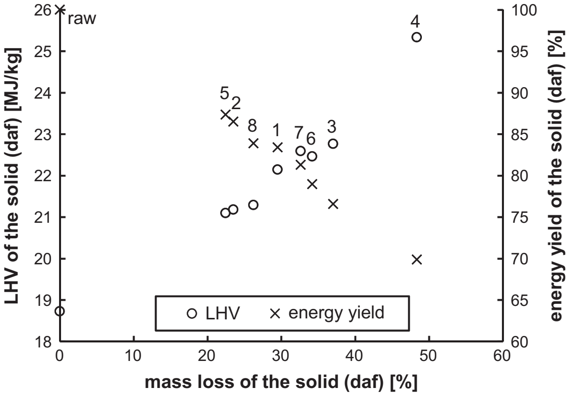

Fig. 5. Dependence of lower heating values (LHVs) and energy yield on the mass loss of the solid.

Table 3
Proximate and ultimate analysis data on dry basis.

Test ID	Δm (%, (daf))	C (wt.%)	H (wt.%)	N (wt.%)	S (wt.%)	O (residue)	Ash (wt.%) at 550 °C	Volatiles (wt.%)	Fixed C (wt.%)
Raw	0.00	49.83	6.36	0.14	0.07	43.12	0.59	83.41	16.12
2	23.51	56.77	6.34	0.17	0.06	35.89	0.99	76.43	22.80
1	29.48	58.00	6.07	0.20	0.07	34.93	0.88	71.20	28.07
3	37.02	61.73	5.82	0.20	0.05	31.47	0.92	66.81	32.46
4	48.36	65.39	5.61	0.21	0.07	27.57	1.49	56.82	42.03
5	22.44	55.90	6.05	0.18	0.05	37.12	0.90	74.72	24.58
6	34.18	59.62	5.77	0.19	0.07	33.63	0.95	68.43	30.84
7	32.61	59.40	5.80	0.18	0.04	33.81	0.96	68.40	30.83
8	26.22	57.02	6.24	0.17	0.06	35.77	0.85	72.76	26.50
9	23.67	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 4
Ash composition (at 550 °C) of raw beechwood and the torrefied product of test 3.

Test ID	Al_2O_3 (wt.%)	CaO	Fe_2O_3 (wt.%)	K_2O (wt.%)	MgO (wt.%)	Mn_2O_3 (wt.%)	Na_2O (wt.%)	P_2O_5 (wt.%)	SiO_2 (wt.%)	TiO_2 (wt.%)	SO_3 (wt.%)	CO_3 (wt.%)	Sum (wt.%)
Raw	0.15	32.81	0.21	25.14	12.37	3.72	0.68	4.41	3.59	0.01	1.95	14.64	99.65
3	0.12	30.93	1.15	25.10	11.84	3.45	0.81	4.21	3.30	0.02	2.01	16.66	99.57

Energy yields are ranging from 69.9% to 87.4%, in line with data of Bridgeman et al. [2] and Pris et al. [15] but below the 90% stated by Bergman et al. [1] and other presentations from ECN. Furthermore, the correlation appears approximately monotonous with notably low energy yield for sample 8 with the high feedstock moisture content.

Proximate and ultimate analysis data of the (torrefied) beechwood as well as the mass loss of the solid on dry ash-free (daf) basis are summarised in Table 3.

The content of carbon, especially of fixed carbon, increases with increasing degree of torrefaction measured as the mass loss of the solid. Simultaneously, hydrogen content is slightly and oxygen and volatiles contents are significantly reduced. Minor species such as nitrogen and sulphur do not exhibit clear trends, which might be caused by fluctuations in their concentration in the feedstock. Additionally, sulphur is close to the quantification limit, hence the significance of these values is limited. However, the nitrogen content tends to behave like the ash content, which is concentrated according to the mass loss of the organic matter. This can be seen by comparison of the ash contents of raw beechwood and sample 3, since that was produced from the same beechwood charge.

A closer look to the ash composition is given in Table 4. Since ash composition measurements were not repeated the presented data have to be treated with caution. The comparison of both samples shows an increase in Fe_2O_3, which is assumed to be caused by abrasion in the reactor. All other components do not reveal significant changes. This indicates that the ash composition is probably not changed significantly by torrefaction.

4.2. Grindability

As stated above, the grindability has been measured in two ways. The results of both are summarised in Fig. 6, the hardgrove grindability index (HGI) on the left ordinate and the crushing ratio on the right. For easier interpretation of the measured values both ordinates are supplemented with additional information: The HGI scale is divided into ranges from "very difficult" to "very easy" grindability and on the crushing ratio ordinate the range of values for Rhenish Lignite according to [9] is indicated.

Grindability in terms of hardgrove grindability index (HGI) as well as in terms of crushing ratio increases almost monotonously with the mass loss of the solid during torrefaction. The raw beechwood exhibits a very poor grindability independent of the grinding process. A mass loss of 20–30% (daf-basis) results in HGIs, which indicate poor grindability. Above 30% mass loss grindability is at least moderate in terms of HGI. In terms of crushing ratio derived by the impact mill, the grindability of torrefied beechwood is significantly improved compared to the raw material. Nevertheless, except for sample 4, its grindability is still below the values achieved with Rhenish lignite with the same mill. Even though sample 4 exhibits an HGI of 122 indicating very easy grindability, in terms of crushing ratio it hardly reaches the lower values of lignite.

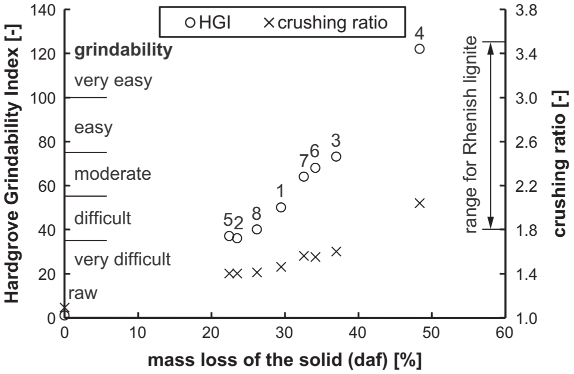

Fig. 6. Grindability of the torrefied and raw beechwood chips.

4.3. Heat demand of torrefaction

The heat consumption per feed mass q_c calculated as described in Section 3.3 is summarised in Fig. 7. The values for q_c range from 249 J/g for test 7 to 986 J/g for test 8, which shows clearly the influence of the feed moisture content as would be expected. For the samples with 10% feed moisture content, q_c ranges from 565 to 705 J/g. The influence of temperature is not very strong and the trend is a slightly lower heat consumption for a higher torrefaction temperature. Residence time has a more significant influence: a higher residence time decreases q_c. Test 9 is difficult to compare to the others since the temperature was high, but the short residence time caused a comparably low mass loss in spite of the feed moisture of 0%. However, due to the high mass flow, measurement uncertainties have less influence for this test.

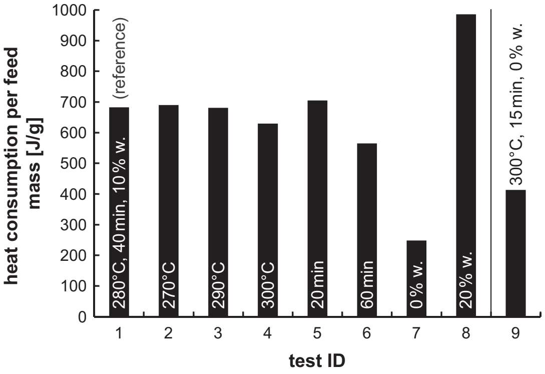

Fig. 7. Dependence of heat consumption per feed mass (q_c) on the torrefaction conditions (see Table 2).

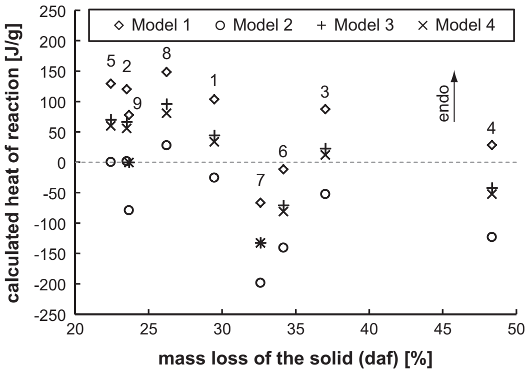

Fig. 9. Calculated heat of reaction for all tests.

These data are already helpful for designing a large scale torrefaction plant, but since exothermic reactions might occur, the heat of reaction is of even larger interest. The integral heat of reaction has been calculated with four different models (compare Section 3.3) for each test. To illustrate the shares of different effects in the heat absorption for these different models, all terms of Eq. (8) are shown in Fig. 8 for the reference test. In this diagram one pattern always marks the same effect with the same value. The illustration shows that for the reference test the measured q_c is similar to the calculated heat of the four models. In this calculation moist wood modelling (difference Model 3 vs Model 4) does not have a great influence. Enthalpy of vaporisation of the moisture accounts for a substantial fraction, but is the same for all models. The most significant difference between the models results from the heat capacity of the solid for temperatures above 147 °C. As shown in Eq. (8), the integral heat of reaction is calculated by the difference between the measured q_c and the calculated heat for each model. Thus, Model 2 yields a slightly exothermic heat of reaction whereas the other models, especially Model 1, yield endothermic heats of reaction.

For all tests the heat of reaction has been calculated in this way. In Fig. 9 these data are plotted against the mass loss of the solid on dry ash-free basis. The plot shows calculated heats of reaction from −199 J/g (exothermic) to 148 J/g (endothermic) with a span of roughly 130 J/g between Model 1 and Model 2 for each specific test. A slight trend to more exothermic reactions for samples with a higher mass loss can be found, but significant fluctuations call for a closer look on the details. Tests 1–4, the temperature variation, show a clear trend to more exothermic reactions for samples with higher mass loss. For test 2 all models yield an endothermic heat of reaction whereas the heat of reaction is probably exothermic for test 4. The variation of the residence time (tests 5, 1 and 6) reveals a significant trend to a more exothermic heat of reaction for an increased residence time. Even more significant is the effect of the moisture content. The reduced feed moisture (test 7) yields a clearly exothermic heat of reaction whereas the increased feed moisture (test 8) yields a clearly endothermic behaviour. Due to the higher mass flow, uncertainties are lower for the heat of reaction derived for test 9. This test is difficult to compare to the others due to very different parameters, however it confirms the order of magnitude lying almost perfectly on the border between an endothermic and exothermic heat of reaction.

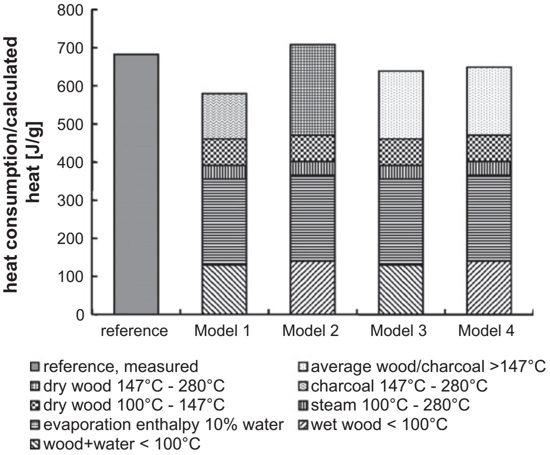

Fig. 8. Measured q_c for the reference test and calculated heat for heating-up the feed.

The remarkable exothermic behaviour of tests 6 and 7 can be explained by the same effect. A reduced moisture content increases the residence time of the biomass at torrefaction temperature. Additionally, the probability of volatile reactions with the solid mass is increased in both cases, since test 6 gives them simply more time and test 7 leads to a reduced steam flow flushing the volatiles out of the reactor. According to Gomez et al. [14] these reactions of volatiles with the solid product cause a more exothermic behaviour, which was also observed by Rath et al. [16]. Both publications investigated the heat of pyrolysis of wood via differential scanning calorimetry and found slightly endothermic reactions for up to about 260 °C. In case of crucibles with lid allowing for secondary reactions between volatiles and solid reactions become increasingly exothermic with temperature increasing to about 310 °C.

Literature data on the heat of reaction of torrefaction are quite rare. Prins [17] and van der Stelt [18] derived a heat of reaction by balancing the chemical energy content of feed vs. that of volatiles and solid product. Prins found an endothermic heat of reaction of 87 (±449) J/g for the torrefaction of willow at 250 °C with a residence time of 30 min causing a mass loss of the solid of 12.8%. For willow at 300 °C, 10 min resulting in a mass loss of 33.2% Prins reported 124 (±400) J/g. The relatively large uncertainties result from the measurement uncertainties of the heating values. Van der Stelt did those experiments with beechwood and discussed the problems of the imperfect mass balance, while Prins did not. Depending on the scenario what happened to the mass missing to 100% he comes out with heats of reaction ranging from −1516 J/g to 1160 J/g for beechwood torrefaction at 280 °C for 30 min resulting in a mass loss of the solid of 27%. Considering the different approach of this work and the partially wide spans of heats of reaction in the literature, the determined heats of reaction fit well to the available literature data.

Van der Stelt determined additional data for the heat of reaction via temperature measurements in large particles of up to 30 mm diameter. These data are not directly comparable to those mentioned above since they represent no integral heat of reaction, but more or less the heat of reaction at torrefaction temperature. Taking into account the findings of Rath et al. [16] and Gomez et al. [14], a more exothermic heat of reaction can be expected for this non-integral examination. Keeping these considerations in mind, van der Stelt's (exothermic) values for beechwood of − 130 J/g (240 °C, 30 min, 18% mass loss) and − 230 J/g (280 °C, 30 min, 32% mass loss) fit well to the determined integral heats of reaction.

5. Conclusion

A continuously working torrefaction reactor was used to conduct a parametric study of beechwood torrefaction. Besides ultimate and proximate analysis of the products, grindability tests have been performed and additionally the heat of reaction was determined. Heating values are in line with literature data and are almost monotonously increasing with the mass loss of the solid (dry ash-free basis). Energy yield is monotonously decreasing on this basis, therefore the mass loss of the solid seems to be a reasonable indicator for the degree of torrefaction, at least for comparison of results obtained with the same feedstock. Grindability was found to be dependent on the degree of torrefaction. In terms of hardgrove grindability index (HGI) a moderate grindability was found for mass loss of the solid greater than 30% with very easy grindability for 48% mass loss. A test procedure similar to the impact grindability index (PMI), which is used to assess the grindability of lignite by beater wheel mills, revealed poor grindability for practically all samples.

The integral heat of reaction was determined with a different approach compared to literature, namely measurement of the heat consumption (q_c) instead of balancing entering and leaving heating values. However, the results fit well to literature data and the uncertainty tends to be lower with this method. Depending on the torrefaction parameters the heat of reaction appears to be slightly endothermic to slightly exothermic. Heat release increases for more severe torrefaction and also remarkably for increased residence time. The reason for this is supposed to lie in secondary reactions of released volatiles with the solid product.

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